NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 355

COMPARATIVE FLIGHT PERFORMANCE WITH AN N. A. C. A. ROOTS SUPERCHARGER AND A TURBOCENTRIFUGAL SUPERCHARGER

By OSCAR W. SCHEY and ALFRED W. YOUNG

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AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Symbol	Unit	Symbol
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of one kilogram	kg	weight of one pound	lb.
Power	P	kg/m/s		horsepower	hp
Speed		km/hr	k. p. h.	mi./hr.	m. p. h.
		m/s	m. p. s.	ft./sec.	f. p. s.

2. GENERAL SYMBOLS, ETC.

W, Weight, $=mg$

g, Standard acceleration of gravity $=9.80665$ m/s^2 $=32.1740$ ft./sec.^{2}

m, Mass, $=\frac{W}{g}$

ρ, Density (mass per unit volume).

Standard density of dry air, 0.12497 (kg-m^{-4} s^2) at 15° C and 760 mm $=0.002378$ (lb.-ft.$^{-4}$ sec.^{2}).

Specific weight of "standard" air, 1.2255 kg/m^3 $=0.07651$ lb./ft.^{3}

mk^2, Moment of inertia (indicate axis of the radius of gyration, k, by proper subscript).

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord length.

b/c, Aspect ratio.

f, Distance from C. G. to elevator hinge.

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed.

q, Dynamic (or impact) pressure $=\frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L=\frac{L}{qS}$

D, Drag, absolute coefficient $C_D=\frac{D}{qS}$

C, Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

R, Resultant force. (Note that these coefficients are twice as large as the old coefficients L_C, D_C.)

i_w, Angle of setting of wings (relative to thrust line).

i_t, Angle of stabilizer setting with reference to thrust line.

γ, Dihedral angle.

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension.

e. g., for a model airfoil 3 in. chord, 100 mi./hr. normal pressure, 0° C: 255,000 and at 15° C., 230,000;

or for a model of 10 cm chord 40 m/s, corresponding numbers are 299,000 and 270,000.

C_p, Center of pressure coefficient (ratio of distance of C. P. from leading edge to chord length).

β, Angle of stabilizer setting with reference to lower wing, $=(i_t-i_w)$.

α, Angle of attack.

ϵ, Angle of downwash.

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By Oscar W. Schey and Alfred W. Young

SUMMARY

As there are now several types of superchargers in service, information on the comparative performance obtained with each type of supercharger would be of value in the selection of a supercharger to meet definite service requirements. As a part of the program to obtain this information, the National Advisory Committee for Aeronautics conducted tests, using a modified DH–4M2 airplane with a turbocentrifugal and with a Roots type supercharger. The rate of climb and the high speed in level flight of the airplane were obtained for each supercharger from sea level to the ceiling. The unsupercharged performance with each supercharger mounted in place was also determined.

The results of these tests show that the ceiling and rate of climb obtained were nearly the same for each supercharger, but that the high speed obtained with the turbocentrifugal was better than that obtained with the Roots. The high-speed performance at 21,000 feet was 122 and 142 miles per hour for the Roots and turbocentrifugal, respectively.

INTRODUCTION

For several years supercharging has been used as a means of increasing the engine power for special-purpose airplanes, notably airplanes designed for high altitude flying or racing. Since the demand for engines of high power output has increased, the interest in superchargers has become more widespread and, as a result, several manufacturers are now offering supercharged engines as a part of their regular production.

The superchargers used at present for aircraft service can be conveniently classified as centrifugal, Roots, and vane type. The first two types have been used extensively since the advent of the supercharging of aircraft engines, while the vane type for this service is a more recent development. It is reasonable to expect either that each of these superchargers has a field in which it is superior to the other types, or that one type will meet all the service requirements better than any of the others. To select the type of supercharger best suited for a particular condition of service, or for all service conditions, test data must be obtained to establish the comparative performance with each type.

Although a large amount of data on supercharging are now available and considerable information can be gained from a study of reports on supercharging, it has been impossible to find data of flight tests in which two types of superchargers have been tested under similar conditions. Therefore, as a part of a research program to obtain comparative test data, the National Advisory Committee for Aeronautics conducted tests with a turbocentrifugal supercharger so as to obtain results for comparison with those previously obtained using the same airplane with a Roots type supercharger.

The basis of comparison for these superchargers was the high speed and rate of climb of the airplane as determined with each supercharger for altitudes from sea level to the ceiling. The unsupercharged performance also was obtained for these conditions with each supercharger mounted in place.

DESCRIPTION AND METHOD

The tests with the Roots type supercharger in a modified DH–4M2 airplane have been previously reported in National Advisory Committee for Aeronautics Technical Report No. 327. (Reference 2.) This report includes the test results obtained with the turbocentrifugal supercharger, together with a sufficient amount of data from the tests with the Roots type, so that the performance with the two types of superchargers can be compared.

Both supercharger installations duplicated previous service installations as nearly as possible. The Roots type supercharger installation can be seen in Figure 1 and that of the turbocentrifugal in Figures 2 and 3. The weight of the airplane fully serviced, including all instruments and the pilot, was approximately 4,300 pounds when equipped with the Roots type supercharger and 4,350 pounds with the turbocentrifugal type. The weight added to the airplane by each supercharger installation was 150 pounds and 167 pounds for the Roots and turbocentrifugal types, respectively. These weights include all air ducts and mounting brackets. That there was a greater difference in airplane weights than in supercharger weights was due to the difference in the instrument installations.

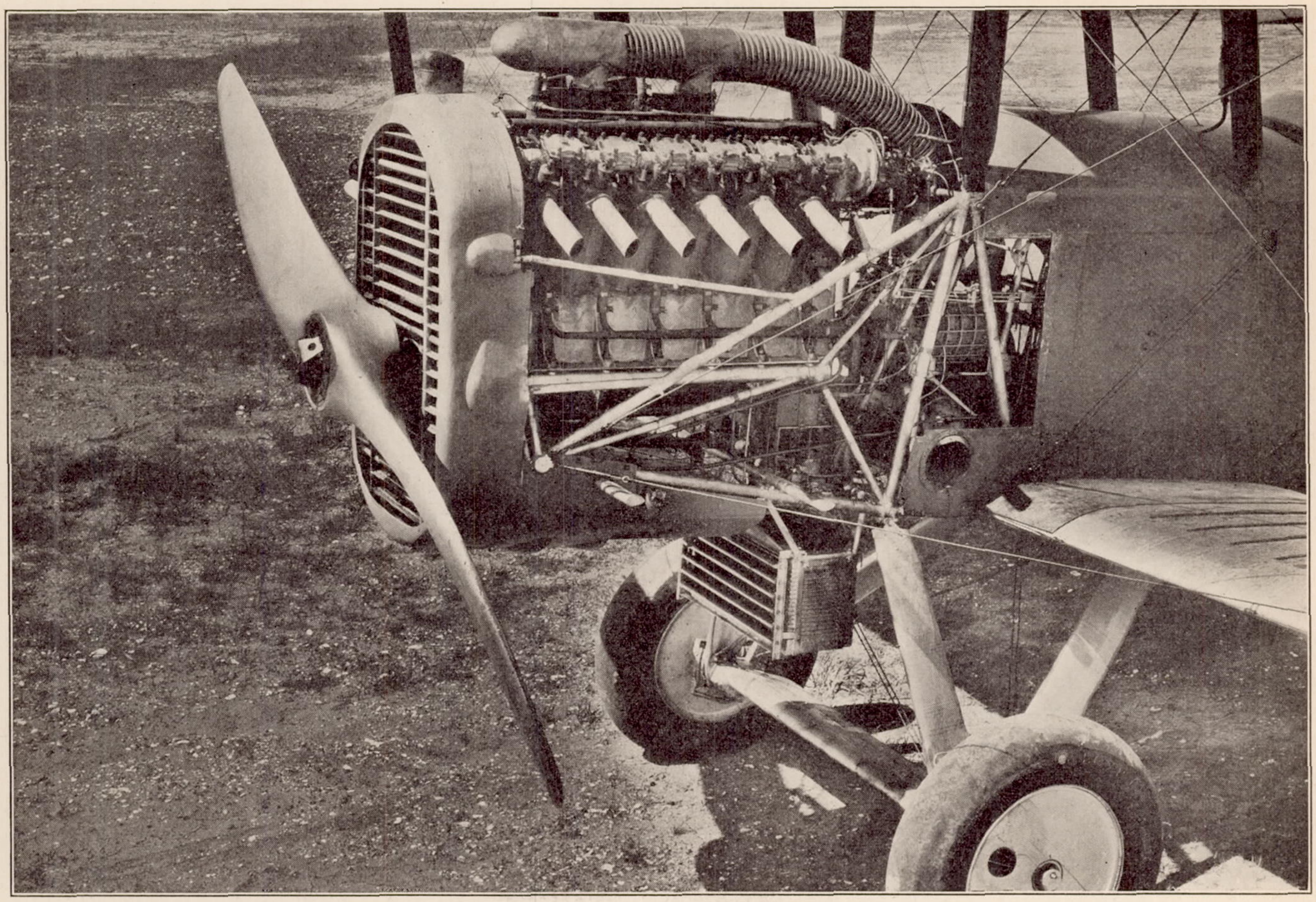

FIGURE 1.—Roots supercharger installation in modified DH-4M2 airplane

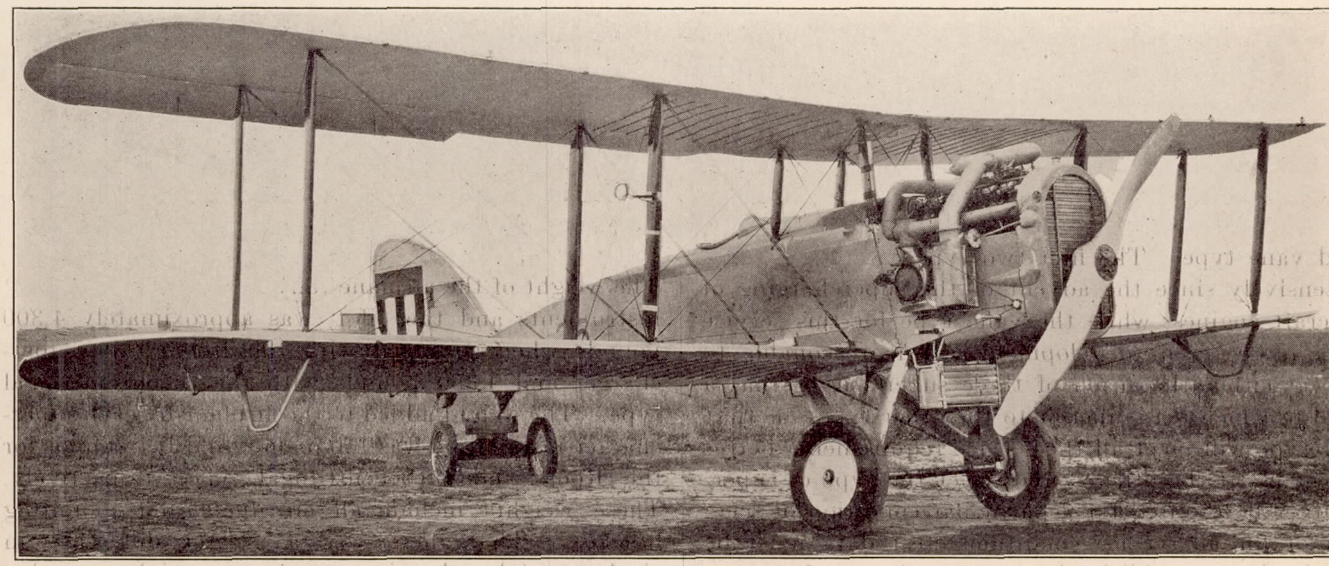

FIGURE 2.—Turbosupercharger installation in modified DH-4M2 airplane

Two Liberty engines were used in these tests, one with the Roots type supercharger and the other with the turbocentrifugal supercharger. A check of the standing revolutions per minute obtained with each engine unsupercharged and with the same propeller showed that there was very little difference in the power developed by the two engines.

The engines were equipped with inverted Stromberg NA–L5A carburetors, having 1⅝-inch diameter chokes and No. 42 drill size jets. Domestic aviation gasoline to which had been added 5 cm^3 of ethyl fluid per gallon was used in all these tests. A booster radiator, shown in Figures 1, 2, and 3, was used to obtain the additional engine cooling necessary on the supercharged flights. This radiator was used also on the unsupercharged flights.

The Roots supercharger used had a displacement of 0.382 cubic foot per revolution. It was driven through a flexible coupling from the rear of the engine crank shaft. The capacity of this supercharger could be varied by changing the gear ratio between the drive shaft and the supercharger impellers. A description of this type of supercharger and laboratory test results are given in National Advisory Committee for Aeronautics Technical Reports Nos. 230 and 284. (References 1 and 2.) The impeller end clearances used in these tests were somewhat greater than necessary. They had been increased to 0.015 inch because trouble had previously been experienced with contacting between the impellers and the ends of the case. Since the clearances were increased precision type ball bearings have been obtained, and the results of tests with these bearings show that constant impeller end clearances can be successfully maintained with the clearances reduced to 0.010 inch.

A description of the side type of turbocentrifugal supercharger is given in Air Corps Technical Report Serial No. 2365. (Reference 3.) The particular model used in these tests, known as Form F–1A, is rated at 20,000 feet critical altitude (the maximum altitude to which the supercharger could maintain sea level pressure) for an engine of 812 cubic feet displacement per minute. The maximum rotative speed of the impeller is given as 23,150 revolutions per minute. The rotor shaft is mounted in two bearings, a roller bearing between the turbine wheel and the supercharger impeller, and a deep-groove ball bearing at the impeller end of the shaft. These bearings are packed with a light grease, the supply of which is replenished between flights through pressure grease gun fittings. Below the critical altitude the amount of supercharging is controlled by a blast gate on the turbine nozzle box. An air cooler similar to those provided on service installations was used. A metal shield was placed between the supercharger inlet and the bottom of the cooler to prevent the hot gases from the turbine and the warm air from the cooler from entering the supercharger inlet.

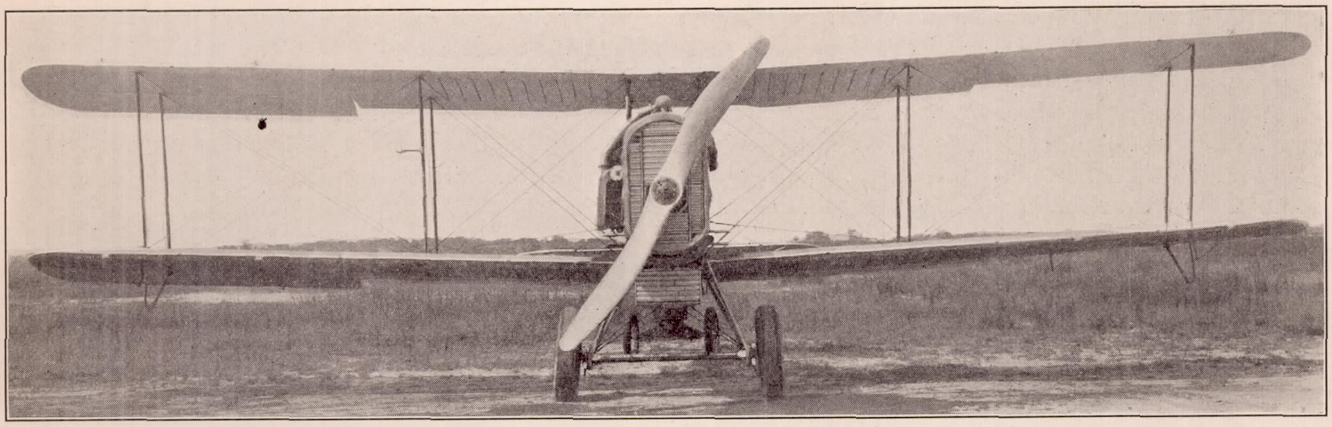

FIGURE 3.—Turbosupercharger installation in modified DH–4M2 airplane

All the instrument readings were recorded automatically during these tests. The readings of the indicating instruments were recorded by photographing the dials of the instruments. For the flight tests both with the turbocentrifugal and the Roots type supercharger the following indicating instruments were used:

(1) Engine tachometer,

(2) Sealed altimeter for measuring carburetor air pressure.

Electrical resistance thermometers for measuring temperature at:

(3) A point under the lower wing (free air),

(4) Inlet to supercharger,

(5) Outlet from supercharger,

(6) Air inlet to carburetor.

In addition to the above, the following instruments were installed and a photographic record of their readings was taken on the flights using the turbocentrifugal supercharger:

(7) Tachometer geared to supercharger rotor.

(8) Pressure gauge connected with turbine nozzle box.

(9) Pyrometer connected in rotation with thermocouples in the exhaust stack, the turbine nozzle box, and just outside the turbine wheel.

Electrical resistance thermometers for measuring temperature at:

(10) Cooler outlet.

(11) Fuel flow meter.

These instruments were mounted on a panel, which formed one end of a light-tight box, and were photographed with a motor-driven motion-picture camera which was mounted at the other end of the box.

For recording the air speeds and atmospheric pressures an instrument was used which gave a continuous photographic record during the flight. Fuel measurements were obtained on the flights with the turbocentrifugal supercharger by the use of a displacement type flow meter to which had been attached a mechanism which produced a photographic record of fuel flow. A Venturi type fuel flow meter was used for measuring the fuel flow on the flights with the Roots supercharger. Because of mechanical difficulties with the recording mechanism the results obtained were not reliable and, therefore, are not included in this report.

A chronometric timer was provided for measuring time and for synchronizing the records obtained with the different instruments.

The supercharger tachometer was driven from a 20 to 1 reduction gear through a standard fitting and flexible cable. A worm was made which replaced the nut on the impeller end of the supercharger shaft, and a 20-tooth gear meshing with this worm was mounted in a small housing which replaced the cover plate on the end of the supercharger case.

A propeller designated as Air Service part No. 065323, which was designed for a supercharged Martin bomber, was used in all these tests. Its diameter was 10.67 feet and its pitch 6.33 feet. This propeller had previously been calibrated on the same airplane by means of a hub dynamometer; therefore the engine power obtained in these tests could be determined from the propeller characteristics. A description of the hub dynamometer used for calibrating this propeller and some of the test results will be found in Natural Advisory Committee for Aeronautics Technical Reports Nos. 252 and 295. (References 4 and 5.)

All of the instruments were calibrated before and after the tests with each supercharger. The accuracy of the measurements is estimated to be as follows:

Engine speed, within ± 10 revolutions per minute.

Supercharger speed, within ± 100 revolutions per minute.

Carburetor air pressure, within ± 0.05 inch Hg.

Atmospheric pressure, within ± 0.05 inch Hg.

Air speed, within ± 2 miles per hour.

Exhaust gas temperatures, within $\pm 15°$ F.

Temperatures measured with electrical resistance thermometers, within $\pm 2°$ F.

Fuel flow, within ± 2 per cent.

Turbine nozzle box pressure, within ± 0.3 pound per square inch.

A comparison of the high speed and rate of climb of the airplane obtained with the two types of superchargers was selected as the best method for evaluating the merits of each supercharger. Before the best rate of climb was determined, without a rate-of-climb meter, the rate of climb obtained at several different air speeds was determined, and from a plot of this, for each altitude, the air speed giving the best rate of climb was selected. This was the method used for the tests with the Roots supercharger. Additional information on this method and a discussion of the tests with the Roots supercharger can be found in National Advisory Committee for Aeronautics Technical Report No. 327. (Reference 6.) For the first part of the tests with the turbocentrifugal supercharger the same method was used. The results obtained were compared with similar results using a rate-of-climb meter as a guide for the pilot. As both methods gave practically the same results, representative flights could be selected from those obtained with either method.

During all supercharged flights the pilot was instructed to maintain sea-level pressure at the carburetor to the greatest possible altitude. With the Roots supercharger the carburetor pressure was regulated by discharging the excess air through a by-pass valve, which was gradually closed with increasing altitude until at the critical altitude it was completely closed. With the turbosupercharger the carburetor pressure was regulated by varying the amount of engine exhaust gases permitted to escape from the nozzle box into the atmosphere without passing through the turbine rotor.

The unsupercharged flights were made with a supercharger installed and operating, but with the control set to give the least possible supercharging effect.

The flight test data were reduced to the conditions of standard atmosphere according to the Lesley method given in National Advisory Committee for Aeronautics Technical Report No. 216. (Reference 7.)

RESULTS AND DISCUSSION OF RESULTS

The results of this investigation are presented in the form of tables and curves. The test data contained in the tables have been plotted so that the comparative performance obtained with the turbocentrifugal and the Roots type of supercharger can be readily appreciated. Tables I to III contain the information obtained in tests with the turbocentrifugal supercharger, while Tables IV to VI contain similar information obtained in tests previously conducted with a Roots type supercharger. The tables and other information regarding the tests with the Roots type supercharger have been taken from National Advisory Committee for Aeronautics Technical Report No. 327. (Reference 6.)

Figure 4 shows the time-of-climb and the rate-of-climb curves for the six flights for which performance data are given in the tables. Although the flight data shown are the best obtained with either supercharger, a greater number of satisfactory flights were made with the Roots type than with the turbocentrifugal; therefore, the data for the Roots type are on a slightly more favorable basis. It is evident that the turbo-supercharged flights correspond more nearly to flight No. 4, using the Roots supercharger with the 3:1 drive-gear ratio, than to flight No. 5, using the 2.4:1 drive ratio. Flight No. 5 shows that when the drive-gear rate of climb than flight No. 6, unsupercharged, with the Roots supercharger installed. This might be expected, since the turbosupercharger installation added an appreciable amount of frontal area. The poor rate of climb at the beginning of flight No. 3 was probably caused by the fact that the air speed for this part of the flight was higher than it should have been, as can be seen in Figure 5.

The air speed in climb and the high speed in level flight are shown in Figure 5. During the tests with the turbosupercharger, flights were made at the air speeds which were found best with the Roots supercharger, but these air speeds did not give the best rate of climb, particularly for the higher altitudes. For the lower altitudes the difference in air speed shown for flights Nos. 1 and 4 is without any particular significance, as

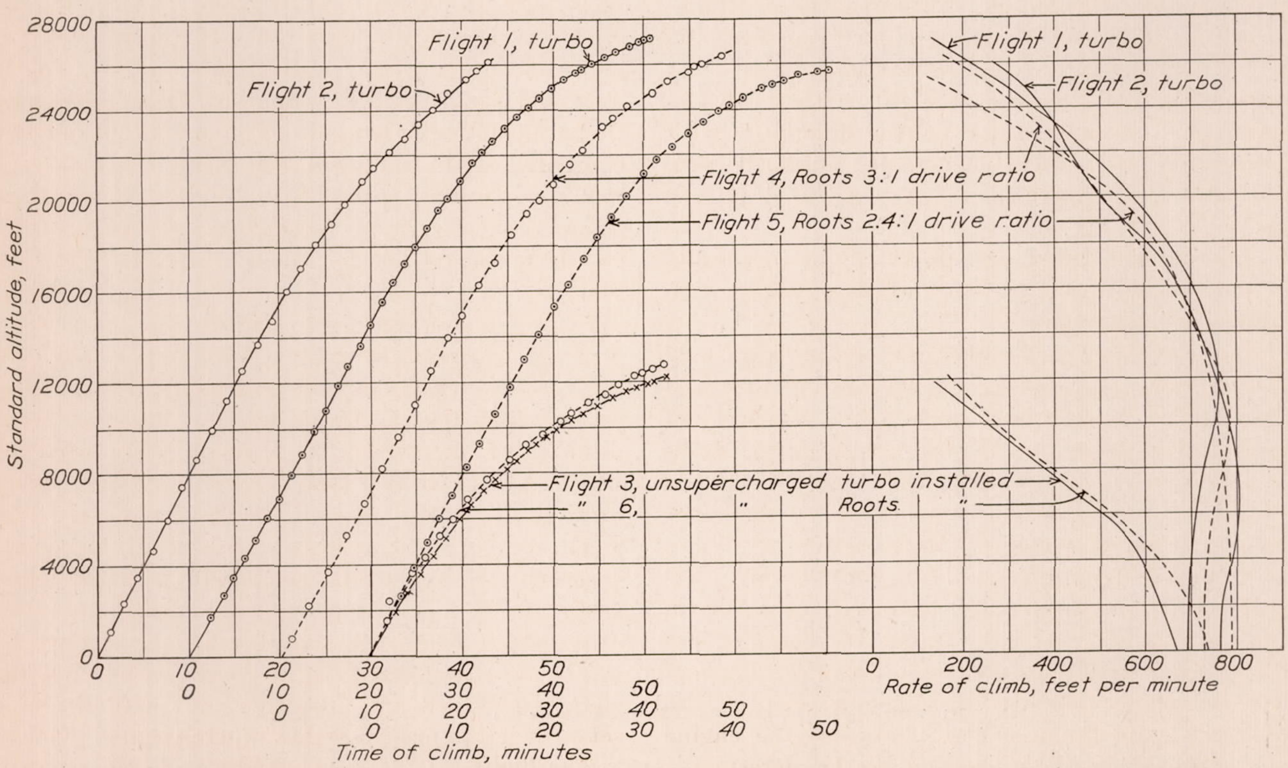

FIGURE 4.—Climb performance of DH-4M2 airplane with the turbosupercharger and with the Roots type supercharger for two drive-gear ratios. Also unsupercharged but with a supercharger installed

ratio of the Roots supercharger was reduced the rate of climb at the lower altitudes was improved slightly, but only with a loss in performance at higher altitudes. Flights Nos. 1 and 2, with the turbosupercharger, are considered to complement each other in showing the best rate of climb, for the air speed giving the best rate of climb was not used at all altitudes in either flight. Although the differences in ceiling and rate of climb with the two superchargers are no greater than those between successive flights with either supercharger, what differences there are indicate slightly better performance with the turbosupercharger.

Flight No. 3, unsupercharged, with the turbosupercharger installed shows slightly lower ceiling and poorer the air speed giving the best rate of climb is much less critical for these altitudes. At the higher altitudes it will be noted that the air speed giving the best rate of climb with the turbosupercharger increases rapidly. All turbosupercharged flights showed this characteristic.

The curves of high speed in level flight, also shown in Figure 5, were drawn from the best data obtained on many flights. There were not enough points to locate the curves exactly, but it was established that the speed in level flight was greater when using the turbo-supercharger, and that the difference increased with increase in altitude. At 21,000 feet the high-speed performance was 122 and 142 miles per hour, for the

Roots and turbocentrifugal, respectively. The high-speed unsupercharged performance was practically the same with both supercharger installations. The high-speed performance obtained with the turbocentrifugal supercharger, even with its increased frontal area, is a strong argument in favor of this type of supercharger for airplanes traveling at high altitudes.

The curves of engine speed (fig. 6) follow very closely the shape of the air-speed curves in Figure 5. The low engine speeds at the ground were due to the use of a much larger propeller than is customary for unsupercharged work in order to hold down the engine speed to less than 1,800 revolutions per minute at altitude on the supercharged flights.

Air temperatures are shown in Figure 8 for both flight No. 2 with the turbocentrifugal supercharger and flight No. 4 with the 3:1 drive ratio Roots supercharger. It will be noted that for both superchargers the temperature at the supercharger inlet was higher than the atmospheric temperature, although in each case the inlet was located where it was thought there would be a minimum heating effect from the engine. At the completion of the tests with the Roots type supercharger it was believed that the higher temperatures recorded at the supercharger inlet were incorrect and were caused by conduction of heat from the supercharger case to the resistance thermometer. The difference in temperature was so much greater, however,

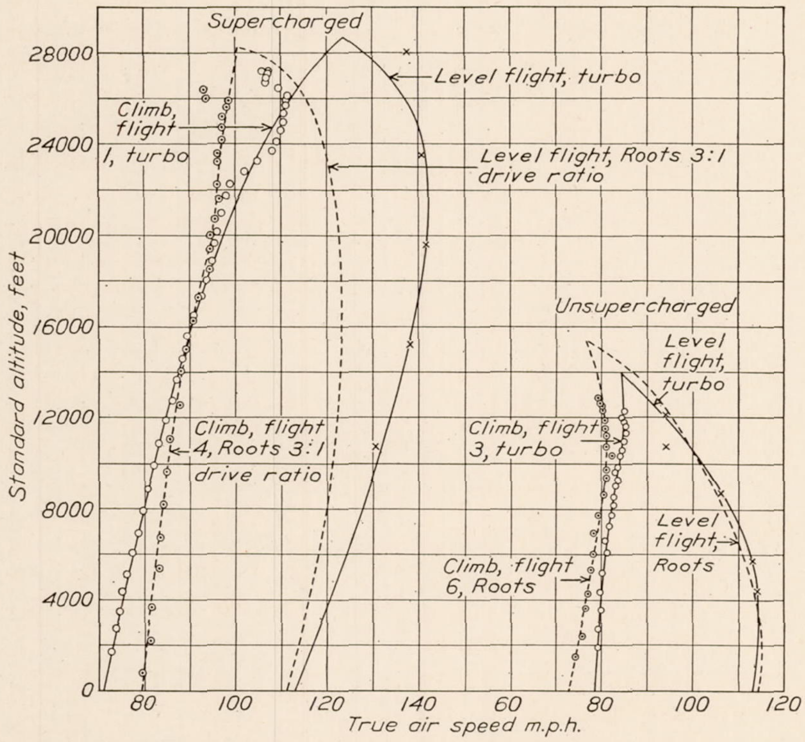

FIGURE 5.—Air speed in climb and level flight with the turbosupercharger and with the Roots type supercharger using a 3:1 drive-gear ratio. Also unsupercharged but with a supercharger installed

The engine power in climb is shown in Figure 7. The difference in engine power at altitude was due to the difference in engine speed as well as to the difference in the power each supercharger cost the engine.

Computations based on experimental data show that the Roots type supercharger with 3:1 drive-gear ratio required 24 per cent of the brake horsepower developed by the engine at an altitude of 22,000 feet. From the experimental data available on the effect of back pressure on engine power and from back pressures obtained with the turbosupercharger in these tests, computations show that the turbosupercharger did not reduce engine brake horsepower more than 14 per cent at an altitude of 22,000 feet. Similar computations for an altitude of 10,000 feet show a reduction of 12 and 6 per cent for Roots and turbocentrifugal, respectively.

in the tests with the turbosupercharger, where the thermometer had been carefully insulated from nearby parts, that it is now believed that both superchargers were receiving air which had been heated by the engine and radiator. The rise in temperature in passing through the supercharger does not appear to have been any greater with the turbosupercharger than with the Roots, but the inlet temperatures of the turbosupercharger were much higher, and consequently the final temperatures. It seems probable that if the inlet pipe could be placed where it would receive air at atmospheric temperature, the temperature after compression might be low enough to make the use of an air cooler unnecessary. The air cooler used with the turbosupercharger had a much greater cooling effect than the carburetor inlet duct used with the Roots supercharger, and as a result the air temperatures at the carburetor, in spite of the higher temperatures at the supercharger outlet, were somewhat lower with the turbosupercharger. The cooling obtained in the air duct from the cooler to the carburetor was negligible in tests with the turbosupercharger.

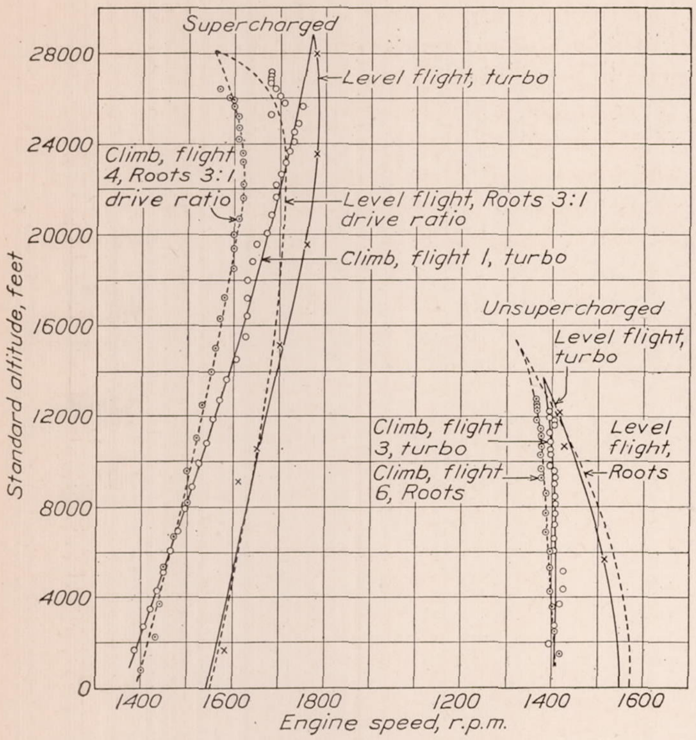

FIGURE 6.—Engine speed in climb and level flight with the turbosupercharger and with the Roots type supercharger using a 3:1 drive-gear ratio. Also unsupercharged but with a supercharger installed

The atmospheric and carburetor air pressures for flights with the two types of superchargers, both supercharged and unsupercharged, are shown in Figure 9. The uniform difference in atmospheric pressures for flights Nos. 1 and 4, for corresponding standard altitudes is due to the fact that flight No. 1 was made on a warmer day than flight No. 4. The critical altitude is not as sharply defined for the turbosupercharger as for the Roots, for a change in air speed changed the critical altitude, and the pilot was increasing the air speed constantly through this range of altitude in order to maintain the best rate of climb.

On flights Nos. 3 and 6 (fig. 9), both unsupercharged, the carburetor air pressures were slightly higher than atmospheric pressures, although the supercharger controls were set to give the least possible supercharging effect. The maximum differences between atmospheric pressure and carburetor pressure were 0.2 and 1.0 inch of Hg for the Roots and turbocentrifugal, respectively.

Figure 10 shows the speed of the supercharger rotor for two flights. As the supercharger tachometer did not register at the lower range of altitudes in flight No. 1, data obtained on another flight are also shown in Figure 10. During these full-throttle climbs the speed reached approximately 28,000 revolutions per minute, which is 5,000 revolutions per minute more than the rated speed for this rotor.

In Figure 11 are shown fuel consumption data for unsupercharged flight No. 3 and supercharged flight No. 1, both full-throttle climbs. That the fuel consumption per brake horsepower per hour should increase with altitude could be expected, because the ratio of friction to brake horsepower increases with altitude. The total fuel consumed per hour increased from 220 pounds at sea level to 265 pounds at the critical altitude.

As the data obtained for fuel consumption in level flight were not satisfactory, an estimate of this consumption was made on the basis that the specific fuel consumption at any altitude would be the same in climb as in level flight, and that the power varied directly as the engine speed. On the basis of these assumptions the total fuel consumed per mile increased for both the supercharged and the unsupercharged condition for altitudes from sea level to 8,000 feet; above 8,000 feet, however, the fuel consumption for the unsupercharged engine increased, while that of the supercharged remained practically the same.

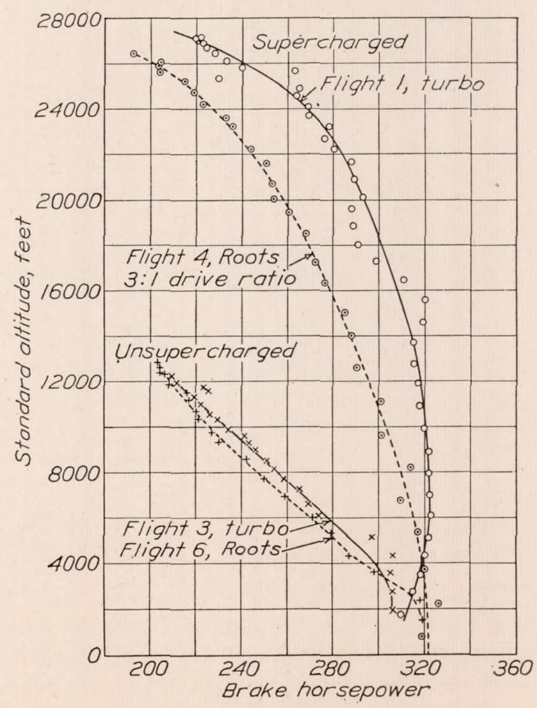

FIGURE 7.—Power delivered to the propeller in climb, with the turbosupercharger and with the Roots type supercharger using a 3:1 drive-gear ratio. Also unsupercharged but with a supercharger installed

These tests showed that the acceleration of the engine equipped with a turbosupercharger was sluggish. This was due to the time necessary for the turbosupercharger to reach an effective speed because of the inertia of its rotating parts.

It may be well to mention that the airplane when equipped with the turbosupercharger was operating under the disadvantage of increased frontal area, and when equipped with the Roots supercharger under the disadvantage of large supercharger impeller end clearances, which resulted in high slip speeds and consequently high discharge air temperatures.

Some trouble was experienced with cracking of the exhaust gas ducts in the tests with the turbosupercharger. As this was caused by excessive vibration the difficulty could be remedied by the use of less rigid ducts. Similar trouble had previously been experienced with the carburetor air ducts in tests with a Roots supercharger. The use of flexible metal hose for carburetor air ducts, as shown in Figure 1, eliminated this difficulty.

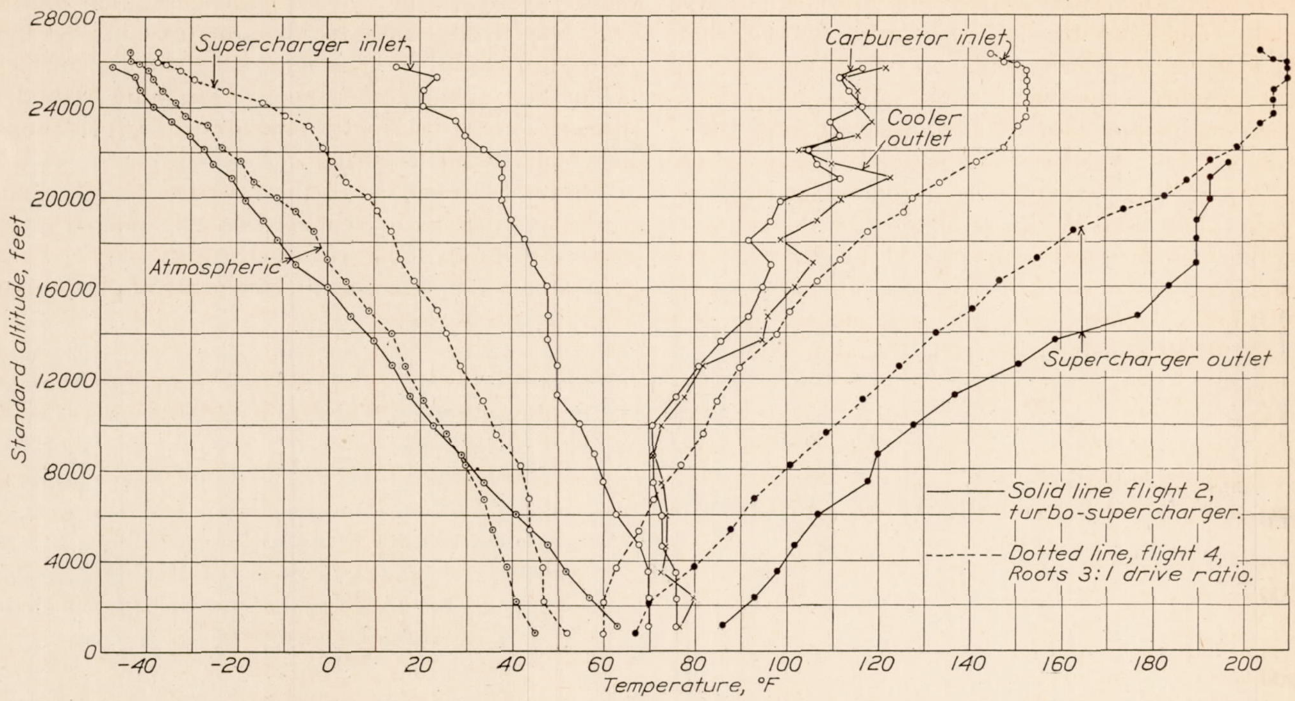

FIGURE 8.—Air temperatures during supercharged climbs, with the turbosupercharger and with the Roots type supercharger using a 3:1 drive-gear ratio

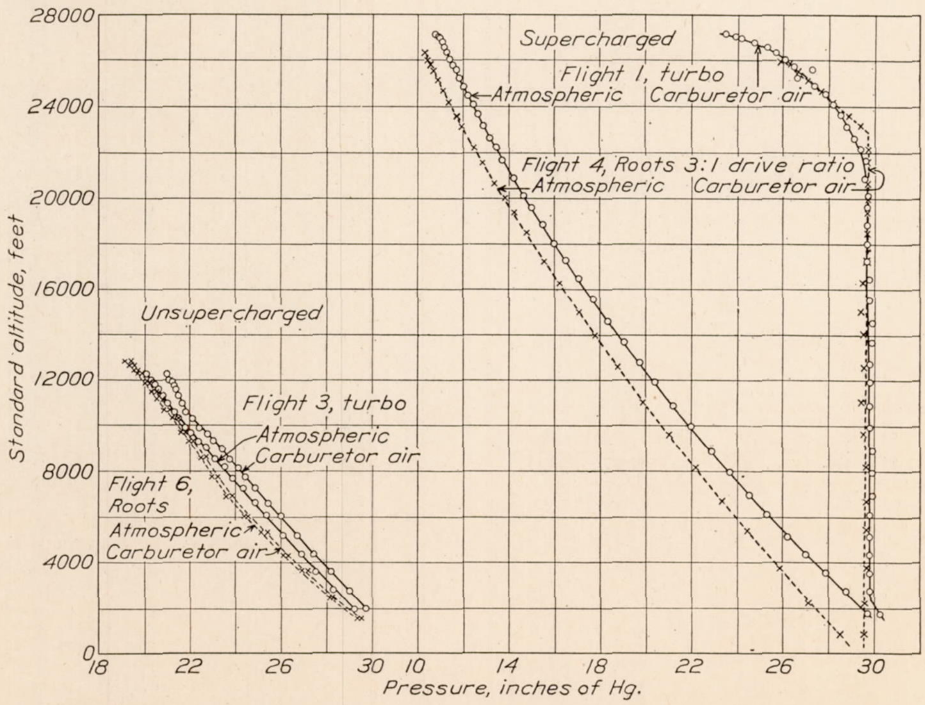

FIGURE 9.—Atmospheric and carburetor air pressures in climb with the turbosupercharger and with the Roots type supercharger using a 3:1 drive-gear ratio. Also unsupercharged but with a supercharger installed

During the tests with the turbosupercharger the engine exhaust valves would stick frequently, which resulted in decreased performance. This trouble was most pronounced when the engine had been standing idle for several weeks. An inspection of these valves showed they were badly pitted and corroded. Tests recently completed by the Air Corps showed that ethyl fluid, as used in gasoline to reduce detonation, causes exhaust valves and valve guides to corrode after an engine has been left in storage for some time. (Reference 8.) Whether the sticking of valves when using the turbosupercharger was due to the effect of the ethyl fluid used in the gasoline or to the exhaust valves being constantly surrounded by the hot exhaust gases, or to both of these, is difficult to say. This trouble, however, was not experienced in tests with the Roots supercharger using the same fuel.

CONCLUSIONS

The results of these tests show that for the two supercharger installations tested the rate of climb and ceiling obtained were practically the same.

The sea level high speed showed no appreciable difference. However, as the altitude of operation was increased the turbocentrifugal supercharger gave the higher speed. The difference in speed between the two types of superchargers increased gradually, reaching 20 miles per hour at an altitude of 21,000 feet.

The high-speed performance of airplanes flying long distances could be greatly improved by supercharging and flying at higher altitudes.

The acceleration at high altitudes of the engine equipped with the turbosupercharger was very sluggish. However, the turbocentrifugal supercharger gave a greater improvement in all-around performance than did the Roots.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *February 25, 1930.*

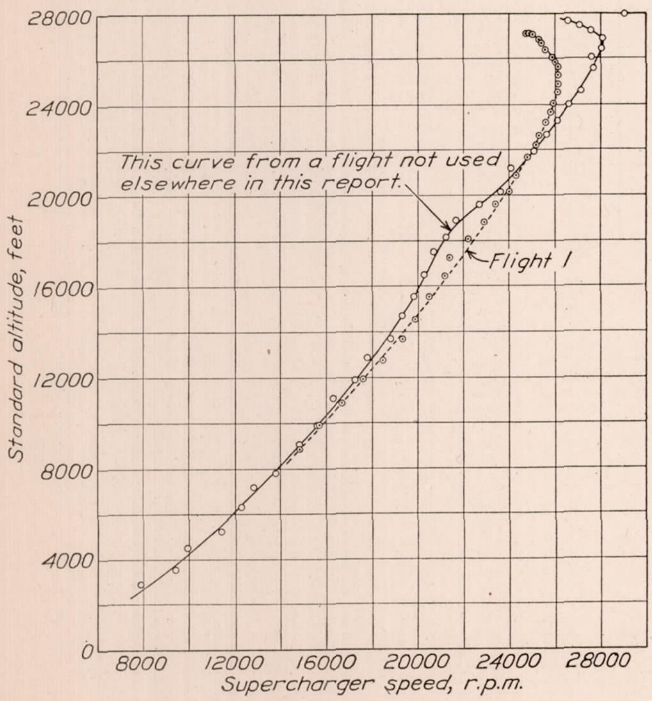

FIGURE 10.—Turbosupercharger rotor speed in climb

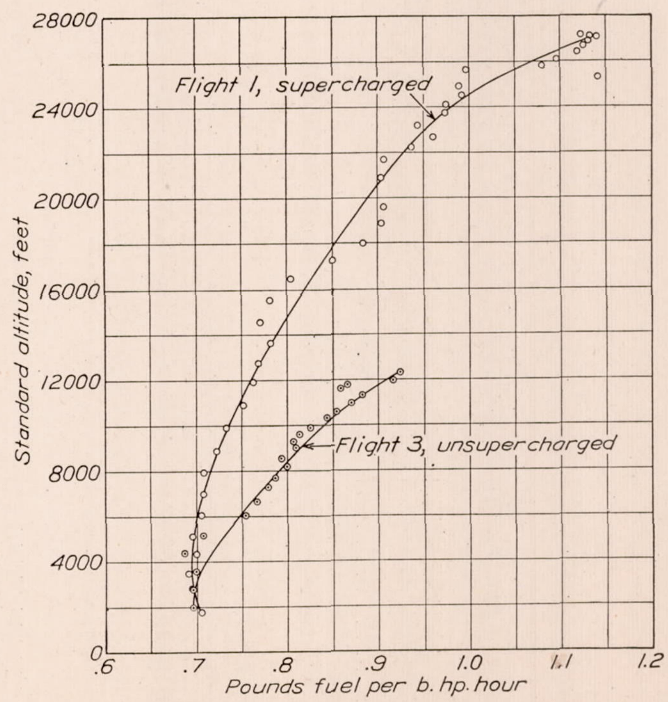

FIGURE 11.—Fuel comsumption during full-throttle climb using the turbosupercharger. Also unsupercharged but with the supercharger installed

TABLE I.—FULL-THROTTLE CLIMB WITH TURBOCENTRIFUGAL SUPERCHARGER (FLIGHT NO. 1)

Reading No.	Corrected time, minutes	Atmospheric temperature, ° F.	Atmospheric pressure, in. Hg	Atmospheric density, pounds per cubic foot	Standard altitude, feet	Engine speed, revolutions per minute	True air speed, miles per hour	V/nD	Brake horsepower	Temperature at supercharger inlet, ° F.	Temperature at supercharger outlet, ° F.	Temperature at carburetor inlet, ° F.	Pressure at carburetor inlet, in. Hg	Supercharger speed, revolutions per minute
1	2.45	81	29.65	0.0727	1,725	1,385	72.5	0.432	310	83	108.5	----------	30.20	----------
2	3.87	79.5	28.72	.0706	2,725	1,405	73.5	.431	315	83	114.5	98.5	29.78	----------
3	4.98	76	27.85	.0690	3,475	1,420	74.5	.432	318.5	82	120.5	98.5	29.78	----------
4	6.19	71.5	26.97	.0673	4,325	1,435	75	.431	320	80	122	95.5	29.78	----------
5	7.35	68.5	26.15	.0657	5,100	1,450	76	.432	322	79	122	92	29.78	----------
6	8.65	65.5	25.30	.0639	6,025	1,465	77	.433	323	77	123.5	90.5	29.78	----------
7	9.99	64	24.50	.0621	6,950	1,480	78.5	.437	322	76	126.5	90.5	29.88	----------
8	11.32	61	23.65	.0602	7,950	1,495	79.5	.438	322	74	132.5	90.5	29.88	----------
9	12.54	58	22.82	.0585	8,875	1,510	80.5	.439	322	73	138.5	90.5	29.88	----------
10	13.85	55	21.97	.0566	9,925	1,525	82	.443	320	72	145	92	29.78	14,900
11	15.04	51	21.17	.0550	10,850	1,540	83	.444	318	72	151	93	29.78	15,700
12	16.35	48	20.37	.0532	11,900	1,555	84.5	.448	317	70	158	95.5	29.78	16,700
13	17.53	43.5	19.67	.0518	12,750	1,570	86	.452	315	69	168.5	98.5	29.78	17,600
14	18.80	41	19.00	.0503	13,650	1,585	87	.453	315	67	175.5	99.5	29.88	18,500
15	20.04	38	18.32	.0488	14,575	1,605	88.5	.454	319	66	183	101	29.88	19,300
16	21.33	35.5	17.65	.0473	15,550	1,625	89.5	.454	320	66	----------	101	29.78	19,900
17	22.58	32	17.03	.0459	16,450	1,630	91	.460	311	67	----------	99.5	29.78	20,500
18	23.75	28.5	16.46	.0447	17,250	1,630	92.5	.468	299	69	----------	98.5	29.67	21,200
19	24.95	26	15.95	.0436	18,000	1,630	94	.476	291	69	----------	103.5	29.67	21,400
20	26.18	23	15.42	.0424	18,825	1,640	95	.478	289	66	----------	114	29.67	22,200
21	27.45	20.5	14.95	.0413	19,600	1,650	95.5	.477	288	63	----------	122	29.67	22,900
22	28.53	18	14.60	.0406	20,100	1,670	96	.474	293	54	----------	130	29.67	23,400
23	29.84	15	14.15	.0395	20,900	1,680	97	.476	289	49	----------	138	29.57	24,000
24	31.08	12.5	13.70	.0385	21,675	1,690	98	.478	288	48	----------	141	29.57	24,300
25	32.31	10	13.40	.0378	22,200	1,690	99	.483	280	48	----------	146	29.37	24,800
26	33.35	8.5	13.10	.0371	22,650	1,700	102	.495	276	48	----------	143.5	29.07	25,200
27	34.84	7.5	12.85	.0365	23,200	1,710	105	.507	278	46	----------	141	28.80	25,300
28	36.22	6	12.62	.0359	23,675	1,720	108	.518	269	43	----------	138	28.50	25,600
29	37.42	4.5	12.40	.0354	24,075	1,730	109	.520	269	48	----------	135.5	28.20	25,800
30	38.65	3.5	12.15	.0348	24,550	1,730	110	.524	264	53	----------	132.5	27.83	25,900
31	39.96	2	11.98	.0344	24,900	1,740	110.5	.524	265	56	----------	127	27.35	26,100
32	41.36	2	11.80	.0339	25,300	1,680	110.5	.542	230	50	----------	126	26.60	26,100
33	42.64	.5	11.63	.0335	25,650	1,750	111	.523	263	48	----------	124.5	27.25	26,100
34	43.35	−2	11.50	.0333	25,800	1,710	111	.535	240	47	----------	124.5	26.50	26,100
35	44.47	−3.5	11.35	.0330	26,075	1,700	111.5	.541	233	44	----------	124.5	26.05	26,000
36	45.78	−4.5	11.20	.0326	26,400	1,690	109.5	.534	228	43	----------	124.5	25.63	25,900
37	47.03	−4.5	11.08	.0323	26,650	1,680	106.5	.523	224	41	----------	122	25.28	25,600
38	48.52	−6	11.00	.0321	26,850	1,680	106.5	.523	223	41	----------	116.5	24.68	25,400
39	49.55	−7	10.90	.0319	27,025	1,680	107	.525	221	41	----------	111.5	24.17	25,300
40	50.10	−8.5	10.82	.0318	27,100	1,680	107	.525	220	41	----------	106	23.92	25,000
41	50.73	−10	10.75	.0317	27,175	1,680	105.5	.518	222	41	----------	103.5	23.43	24,900

TABLE II.—FULL-THROTTLE CLIMB WITH TURBOCENTRIFUGAL SUPERCHARGER (FLIGHT NO. 2)

Reading No.	Corrected time, minutes	Atmospheric temperature, °F.	Atmospheric pressure, in. Hg	Atmospheric density, pounds per cubic foot	Standard altitude, feet	Engine speed, revolutions per minute	True air speed, miles per hour	V/nD	Brake horsepower	Temperature at supercharger inlet, °F.	Temperature at supercharger outlet, °F.	Temperature at carburetor inlet, °F.	Pressure at carburetor inlet, in. Hg	Temperature in exhaust stack, °F.	Temperature in turbine nozzle box, °F.	Temperature outside turbine wheel, °F.	Nozzle-box pressure above atmospheric pressure, pounds per square inch
1	1.36	63	29.20	0.0741	1,100	1,375	75.5	0.452	303	70	86	76	30.10	1,250	1,170	1,110	2.2
2	2.90	57	27.80	.0714	2,350	1,385	79	.468	296	70	93	76	29.40	1,265	1,245	1,125	2.7
3	4.50	52	26.60	.0690	3,500	1,405	78.5	.461	298	70	98	76	29.40	1,295	1,275	1,200	3.3
4	6.11	48	25.45	.0666	4,650	1,435	79.5	.455	311	68	102	73	29.40	1,295	1,275	1,200	3.8
5	7.72	41	24.15	.0640	6,000	1,435	80.5	.462	296	63	107	73	29.60	1,285	1,270	1,190	4.4
6	9.27	34	22.78	.0612	7,425	1,465	81	.456	304	60	118	71	29.60	1,280	1,280	1,185	5.0
7	10.84	29	21.67	.0589	8,650	1,485	82	.456	304	58	120	71	29.50	1,295	1,280	1,180	5.5
8	12.61	23	20.60	.0566	9,950	1,495	83	.459	297	55	128	71	29.40	1,290	1,280	1,175	6.0
9	14.26	18	19.56	.0543	11,250	1,495	81.5	.448	287	50	137	76	29.40	1,310	1,285	1,170	6.5
10	15.98	14	18.57	.0520	12,600	1,535	83	.446	297	50	151	81	29.40	1,325	1,280	1,165	7.0
11	17.61	10	17.75	.0502	13,700	1,535	84.5	.455	285	48	159	86	29.60	1,320	1,275	1,135	7.5
12	19.23	5	16.97	.0485	14,775	1,575	86	.450	298	48	177	92	29.60	1,315	1,295	1,130	8.5
13	20.90	0	16.11	.0465	16,050	1,585	88	.457	288	48	184	95	29.70	1,310	1,265	1,065	9.0
14	22.33	−7	15.35	.0450	17,050	1,595	89.5	.462	294	45	190	97	29.00	1,320	1,285	1,080	9.0
15	23.94	−11	14.65	.0434	18,125	1,585	87.5	.456	270	43	190	92	27.70	1,280	1,235	1,075	9.0
16	25.73	−14	14.17	.0422	18,975	1,615	98.5	.502	267	40	190	97	28.00	1,290	1,225	1,045	9.0
17	27.26	−18	13.62	.0410	19,825	1,635	102.5	.518	263	38	193	99	27.20	1,290	1,215	1,025	9.0
18	29.04	−21	13.07	.0396	20,850	1,685	103	.504	284	38	193	112	28.00	1,290	1,225	1,025	9.4
19	30.47	−25	12.68	.0388	21,450	1,645	103.5	.518	254	38	197	107	26.20	1,265	1,240	1,000	9.0
20	32.26	−27	12.35	.0379	22,100	1,635	104	.524	238	34	197	105	26.30	1,240	1,200	1,020	9.0
21	33.85	−30	12.00	.0371	22,725	1,645	106.5	.533	238	30	197	112	26.70	1,260	1,235	995	9.4
22	35.47	−34	11.65	.0363	23,375	1,665	107.5	.533	241	28	197	110	26.40	1,275	1,210	990	9.4
23	36.87	−38	11.27	.0355	24,000	1,615	108.5	.555	209	21	197	117	26.50	1,210	1,205	965	9.9
24	38.60	−41	10.92	.0346	24,725	1,685	110	.540	235	21	197	114	26.20	1,225	1,205	985	9.9
25	40.55	−42	10.68	.0339	25,300	1,535	111.5	.598	160	24	197	112	25.80	1,250	1,205	965	10.4
26	41.77	−47	10.40	.0334	25,725	1,685	112	.549	228	15	197	117	25.30	1,220	1,200	960	10.4

TABLE III.—FULL-THROTTLE UNSUPERCHARGED CLIMB WITH TURBOSUPERCHARGER MOUNTED IN PLACE (FLIGHT NO. 3)

Reading No.	Corrected time, minutes	Atmospheric temperature, °F.	Atmospheric pressure, in. Hg.	Atmospheric density, pounds per cubic foot	Standard altitude, feet	Engine speed, revolutions per minute	True air speed, miles per hour	V/nD	Brake horsepower	Temperature at supercharger outlet, °F.	Temperature at carburetor inlet, °F.	Pressure at carburetor inlet, in. Hg.
1	2.97	76.5	29.20	0.0722	1,950	1,395	79	0.467	306	112	96	29.68
2	4.19	73	28.32	.0705	2,750	1,405	79	.464	306	112	93	29.00
3	5.59	71.5	27.55	.0688	3,575	1,415	80	.466	305	103	88	28.20
4	6.95	70	26.82	.0672	4,350	1,425	79.5	.460	306	103	85.5	27.43
5	8.34	68.5	26.08	.0655	5,175	1,425	80	.463	297	103	85.5	26.70
6	9.78	67	25.36	.0639	6,025	1,405	81	.476	273	103	83	25.98
7	11.12	65.5	24.85	.0628	6,600	1,405	80.5	.473	269	100	78	25.45
8	12.50	64	24.32	.0616	7,225	1,405	81.5	.475	265	97	78	24.85
9	13.80	62.5	23.90	.0607	7,700	1,405	82	.482	258	94	78	24.42
10	15.08	61	23.48	.0598	8,175	1,405	82.5	.485	254	91	75	24.10
11	16.04	58	23.10	.0592	8,500	1,405	82.5	.485	251	91	73	23.75
12	17.42	56.5	22.70	.0583	9,000	1,405	83	.488	246	91	70	23.42
13	18.28	53.5	22.35	.0578	9,275	1,405	83.5	.491	243	89	70	23.03
14	19.45	52	22.05	.0572	9,600	1,405	83	.488	241	89	67.5	22.80
15	20.41	49	21.80	.0568	9,825	1,395	83.5	.494	234	89	67.5	22.46
16	21.92	49	21.45	.0559	10,325	1,395	84	.497	229	85	65	22.15
17	23.46	49	21.28	.0555	10,575	1,395	84.5	.500	226	83	65	21.82
18	24.94	49	21.00	.0548	10,975	1,395	85	.503	222	83	62	21.70
19	26.61	49	20.80	.0542	11,300	1,395	85.5	.506	219	80	62	21.54
20	28.13	49	20.60	.0537	11,600	1,405	85	.499	225	77	62	21.38
21	29.30	48	20.45	.0534	11,775	1,405	85	.499	223	77	62	21.38
22	30.56	48	20.35	.0532	11,900	1,385	84.5	.503	211	80	62	21.24
23	31.06	46.5	20.25	.0531	11,950	1,385	84.5	.503	211	80	62	21.10
24	32.63	46.5	20.06	.0526	12,250	1,385	85	.506	209	80	59.5	21.00

TABLE IV.[1]—OPTIMUM ROOTS SUPERCHARGED CLIMB USING THE 3 : 1 DRIVE RATIO (FLIGHT NO. 4)

Reading No.	Corrected time, minutes	Observed atmospheric temperature, °F.	Observed atmospheric pressure, in. Hg	Atmospheric density, pounds per cubic foot	Standard altitude, feet	Observed engine speed, revolutions per minute	Air speed, miles per per hour	V/nD	Brake horsepower	Temperature at supercharger outlet, °F.	Temperature at carbureter inlet, °F. (abs.)	Pressure at carbureter inlet, in. Hg	Brake horsepower corrected to standard pressure and temperature
1	1.22	45	28.40	0.0748	800	1,400	79.5	0.469	319	67	519	29.50	323
2	3.04	41	27.00	.0716	2,200	1,430	81	.467	326	70	519	29.50	329
3	5.23	39	25.80	.0687	3,700	1,440	81.5	.467	320	80	522	29.60	322
4	7.12	36	24.35	.0652	5,350	1,450	83.5	.475	317	88	527	29.60	319
5	9.19	34	23.30	.0626	6,700	1,470	83.5	.469	309	93	530	29.60	310
6	11.11	30	22.10	.0598	8,200	1,500	84	.462	314	101	536	29.60	316
7	12.90	26	20.95	.0572	9,600	1,500	85	.468	301	109	541	29.50	304
8	14.67	21	19.80	.0547	11,050	1,520	85.5	.464	301	117	544	29.40	304
9	16.50	17	18.70	.0521	12,550	1,530	87.5	.472	290	125	549	29.50	292
10	18.45	14	17.75	.0497	14,000	1,550	88	.469	288	133	557	29.50	290
11	20.08	9	17.00	.0482	15,000	1,560	89	.471	285	141	560	29.40	287
12	21.90	4	16.15	.0461	16,300	1,570	91	.478	276	147	566	29.50	278
13	23.57	0	15.50	.0447	17,250	1,580	92	.481	272	155	571	29.70	272
14	25.41	−3	14.75	.0429	18,500	1,600	94.5	.488	268	163	577	29.70	267
15	27.16	−7	14.20	.0416	19,400	1,600	94.5	.488	260	174	585	29.70	260
16	28.54	−11	13.75	.0407	20,000	1,600	94.5	.488	254	183	587	29.70	254
17	30.11	−16	13.30	.0398	20,700	1,610	95.5	.490	253	188	593	29.70	254
18	31.89	−19	12.80	.0386	21,600	1,620	96.5	.491	251	193	601	29.70	252
19	33.33	−23	12.40	.0378	22,200	1,620	96	.489	244	199	607	29.70	244
20	35.41	−26	11.95	.0365	23,200	1,620	96	.489	236	204	610	29.40	230
21	36.63	−31	11.65	.0360	23,600	1,620	96	.489	233	207	612	28.90	228
22	38.17	−33	11.30	.0352	24,200	1,610	97	.497	223	207	612	28.20	219
23	40.93	−36	11.05	.0346	24,700	1,610	97	.497	219	207	612	27.65	215
24	42.66	−38	10.80	.0340	25,200	1,610	97	.497	215	210	612	27.05	213
25	44.92	−39	10.65	.0335	25,600	1,600	98	.505	204	210	612	26.60	202
26	45.60	−41	10.50	.0332	25,900	1,600	98.5	.508	203	210	610	26.25	201
27	46.43	−43	10.40	.0331	26,000	1,590	93.5	.485	204	207	607	25.90	204
28	48.63	−43	10.25	.0326	26,400	1,570	93	.489	192	204	604	25.60	190

[1] Table XIII, National Advisory Committee for Aeronautics Technical Report No. 327.

TABLE V.[1]—OPTIMUM ROOTS SUPERCHARGED CLIMB USING THE 2.4 : 1 DRIVE RATIO (FLIGHT NO. 5)

Reading No.	Corrected time, minutes	Observed atmospheric temperature, °F.	Observed atmospheric pressure, in. Hg	Atmospheric density, pounds per cubic foot	Standard altitude, feet	Observed engine speed, revolutions per minute	Air speed, miles per hour	V/nD	Brake horsepower	Temperature at supercharger outlet, °F.	Temperature at carburetor inlet, °F. (abs.)	Pressure at carburetor inlet, in. Hg	Brake horsepower corrected to standard pressure and temperature
1	3.40	82	28.95	0.0708	2,600	1,405	74.5	0.437	316	101	558	29.50	332
2	4.83	77	27.60	.0683	3,800	1,425	74.5	.431	315	101	555	29.50	329
3	6.30	71	26.35	.0659	5,000	1,435	74	.425	314	103	555	29.50	326
4	7.60	64	25.20	.0639	6,000	1,455	75	.425	317	105	555	29.40	330
5	9.12	60	24.20	.0619	7,050	1,465	75.5	.425	314	109	557	29.40	326
6	10.79	56	23.20	.0597	8,250	1,475	77	.430	309	114	558	29.40	320
7	12.27	52	22.20	.0576	9,350	1,495	78	.430	312	120	561	29.50	322
8	13.89	48	21.20	.0554	10,600	1,515	79	.430	310	126	567	29.50	320
9	15.48	44	20.25	.0533	11,800	1,525	80	.433	304	133	569	29.40	315
10	17.00	40	19.30	.0513	13,000	1,545	81.5	.435	303	141	573	29.40	314
11	18.62	36	18.50	.0496	14,100	1,565	82.5	.435	302	146	578	29.50	312
12	20.32	33	17.70	.0477	15,300	1,575	84	.440	298	154	583	29.50	307
13	21.90	30	17.00	.0461	16,300	1,585	84.5	.440	294	----------	586	29.50	303
14	23.58	27	16.30	.0445	17,400	1,595	86	.445	289	----------	----------	29.50	295
15	25.05	23	15.60	.0430	18,400	1,605	87.5	.450	288	----------	----------	29.50	285
16	26.65	20	15.10	.0418	19,250	1,605	89	.457	272	----------	----------	28.60	269
17	28.32	18	14.55	.0405	20,200	1,615	89.5	.457	269	----------	----------	27.45	267
18	30.08	16	14.05	.0392	21,150	1,615	91	.465	258	----------	----------	26.45	257
19	31.65	15	13.70	.0384	21,750	1,615	92	.470	252	----------	----------	25.80	251
20	33.29	14	13.40	.0376	22,300	1,605	92.5	.475	242	----------	----------	25.20	242
21	35.05	12	13.10	.0369	22,900	1,605	93	.478	236	----------	----------	24.70	235
22	36.77	11	12.85	.0362	23,400	1,595	93.5	.483	227	----------	----------	24.25	226
23	38.47	10	12.60	.0356	23,900	1,595	94.5	.489	222	----------	----------	23.85	221
24	39.51	7	12.40	.0353	24,150	1,595	95	.491	219	----------	----------	23.60	217
25	41.16	7	12.20	.0348	24,550	1,595	95.5	.494	214	----------	----------	23.40	212
26	43.06	5	12.05	.0344	24,900	1,595	95	.491	213	----------	----------	23.20	210
27	44.28	4	11.95	.0342	25,050	1,595	95	.491	213	----------	----------	23.00	210
28	45.50	3	11.85	.0340	25,200	1,595	95.5	.494	210	----------	----------	22.80	208
29	47.10	1	11.70	.0337	25,500	1,595	96	.496	206	----------	----------	22.55	203
30	49.46	1	11.65	.0335	25,650	1,585	96	.494	207	----------	----------	22.40	204
31	50.64	0	11.60	.0334	25,725	1,585	96	.494	207	----------	----------	22.25	205

[1] Table X, National Advisory Committee for Aeronautics Technical Report No. 327.

TABLE VI.[1]—OPTIMUM FULL-THROTTLE UNSUPERCHARGED CLIMB WITH ROOTS SUPERCHARGER MOUNTED IN PLACE (FLIGHT NO. 6)

Reading No.	Corrected time, minutes	Observed atmospheric temperature, °F.	Observed atmospheric pressure, in. Hg	Atmospheric density, pounds per cubic foot	Standard altitude, feet	Observed engine speed, revolutions per minute	Air speed, miles per hour	V/nD	Brake horsepower	Temperature at supercharger outlet, °F.	Temperature at carburetor inlet, °F. (abs.)	Pressure at carburetor inlet, in. Hg	Brake horsepower corrected to standard pressure and temperature
1	1.85	71	29.35	0.0733	1,500	1,415	74	0.432	319	82	539	29.50	314
2	2.11	64	28.15	.0713	2,400	1,405	75.5	.441	318	78	534	28.20	317
3	4.68	60	26.90	.0687	3,600	1,400	76.5	.451	298	75	531	27.20	295
4	6.06	55	26.10	.0673	4,300	1,395	77	.456	287	71	526	26.30	285
5	7.60	50	25.10	.0654	5,300	1,395	77.5	.459	279	65	520	25.40	276
6	9.11	46	24.40	.0640	6,000	1,395	78	.462	271	63	515	24.50	269
7	10.77	44	23.60	.0622	6,900	1,385	78	.465	259	60	512	23.85	256
8	12.80	44	23.00	.0606	7,750	1,385	79	.471	250	60	511	23.20	247
9	15.46	46	22.50	.0590	8,600	1,385	80.5	.480	242	60	512	22.70	237
10	17.35	46	22.00	.0577	9,300	1,375	81	.486	230	60	512	22.15	226
11	19.13	45	21.70	.0571	9,700	1,375	81	.486	227	60	512	21.80	223
12	20.88	44	21.25	.0560	10,300	1,375	82	.492	221	60	512	21.50	215
13	22.18	41	20.90	.0553	10,650	1,375	81	.486	220	60	511	21.10	215
14	23.99	40	20.55	.0545	11,150	1,375	81	.486	217	60	509	20.80	211
15	25.88	40	20.35	.0539	11,450	1,375	80.5	.483	216	60	508	20.50	211
16	27.53	38	20.05	.0533	11,850	1,365	80.5	.487	208	60	508	20.20	203
17	29.11	37	19.70	.0526	12,300	1,365	80	.484	206	59	508	19.90	201
18	29.92	36	19.55	.0523	12,400	1,365	80	.484	204	59	508	19.75	200
19	31.13	34	19.35	.0520	12,600	1,365	79.5	.478	204	58	506	19.50	202
20	32.33	33	19.15	.0517	12,800	1,365	79	.478	203	55	506	19.40	200

[1] Table I, National Advisory Committee for Aeronautics Technical Report No. 327.

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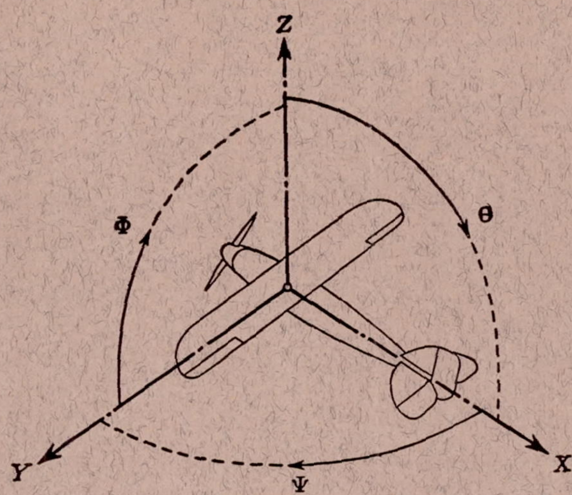

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	rolling	L	$Y \longrightarrow Z$	roll	Φ	u	p
Lateral	Y	Y	pitching	M	$Z \longrightarrow X$	pitch	Θ	v	q
Normal	Z	Z	yawing	N	$X \longrightarrow Y$	yaw	Ψ	w	r

Absolute coefficients of moment

$$C_L = \frac{L}{qbS} \qquad C_M = \frac{M}{qcS} \qquad C_N = \frac{N}{qfS}$$

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter.
p_e, Effective pitch.
p_g, Mean geometric pitch.
p_s, Standard pitch.
p_t, Zero thrust.
p_a, Zero torque.
p/D, Pitch ratio.
V', Inflow velocity.
V_s, Slip stream velocity.

T, Thrust.
Q, Torque.
P, Power.
(If "coefficients" are introduced all units used must be consistent.)
η, Efficiency $= T\,V/P$.
n, Revolutions per sec., r. p. s.
N, Revolutions per minute, r. p. m.
Φ, Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi rn}\right)$

5. NUMERICAL RELATIONS

1 hp = 76.04 kg/m/s = 550 lb./ft./sec.
1 kg/m/s = 0.01315 hp
1 mi./hr. = 0.44704 m/s
1 m/s = 2.23693 mi./hr.

1 lb. = 0.4535924277 kg
1 kg = 2.2046224 lb.
1 mi. = 1609.35 m = 5280 ft.
1 m = 3.2808333 ft.